# Dark matter in the MSSM and its singlet extension

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## Abstract

We briefly review the supersymetric explanation for the cosmic dark matter. Although the neutralino in the minimal supersymmetric model (MSSM), the next-to-minimal supersymmetric model (NMSSM) and the nearly minimal supersymmetric model (nMSSM) can naturally explain the dark matter relic density, the PAMELA result can hardly be explained in these popular models. In the general singlet extension of the MSSM, both the PAMELA result and the relic density can be explained by the singlino-like neutralino. Such singlino-like neutralinos annihilate into the singlet-like Higgs bosons, which are light enough to decay dominantly to muons or electrons, and the annihilation cross section can be greatly enhanced by the Sommerfeld effect via exchanging a light CP-even singlet-like Higgs boson. In this scenario, in order to meet the stringent LEP constraints, the SM-like Higgs boson tends to decay into the singlet Higgs pairs instead of $b\bar{b}$ and consequently it will give a multi-muon signal $h_{SM} \to aa \to 4\mu$ or $h_{SM} \to hh \to 4a \to 8\mu$ at the LHC.

# I. INTRODUCTION

The cosmic dark matter relic density measured by WMAP [1], $0.0945 < \Omega h^2 < 0.1287$ , can be naturally explained by the thermal production of WIMP (weakly interacting massive particle). The neutralino (assumed to be the lightest supersymmetric particle) in the minimal supersymmetric model (MSSM) is a good candidate for the WIMP. Actually, the two events recently reported by the CDMSII [2] can also be naturally explained by such a WIMP [3]. So both the the relic density measured by WMAP and the two events observed by CDMSII can be perfectly explained by the neutralino in the MSSM.

However, the excess of the cosmic ray positron in the energy range 10-100 GeV observed by PAMELA [4] is hard to be explained by the neutralino in the popular MSSM. To explain the PAMELA excess by WIMP annihilation, the WIMP must annihilate dominantly into leptons since PAMELA has observed no excess of anti-protons [4] ( this statement may be not so solid due to the significant astrophysical uncertainties associated with their propagation [5]). Meanwhile, the WIMP annihilation rate must be greatly enhanced (say by the Sommerfeld effect of a new force [6]) relative to the rate required by the relic density if the dark matter is produced thermally in the early universe. These two requirements cannot be satisfied in the MSSM because there is not a new force in the neutralino dark matter sector to induce the Sommerfeld enhancement and the neutralino dark matter annihilates largely to final states consisting of heavy quarks or gauge and/or Higgs bosons [7, 8] (so if it predicts positron excess, it must simultaneously gives antiproton excess).

Note that if supersymmetry is chosen by nature, the MSSM may not be the most favored model to realize it. Actually, since the MSSM suffers from the $\mu$-problem and the little hierarchy problem, some non-minimal supersymmetric models may be equally or better motivated, among which the most intensively studied is the extension of the MSSM by introducing a singlet Higgs superfield. If we do not impose any discrete symmetry to forbid some terms in the superpotential, the model is the general singlet extension of the MSSM. If we impose some discrete symmetry, then we obtain some specified singlet extensions like the next-to-minimal supersymmetric standard model (NMSSM) [9] and the nearly minimal supersymmetric standard model (nMSSM) [10]. As shown by recent studies [11], the nMSSM and NMSSM are unlikely to explain the PAMELA result due to the tight parameter space constrained by various current experiments while the general singlet extension of the MSSM

can perfectly make it. In the general singlet extension of the MSSM, the singlino-like neutralino (the lightest supersymmetric particle) serves as the dark matter, which annihilates to the light singlet-like Higgs bosons. Since the interaction between singlino-like neutralino and singlet-like Higgs bosons is not suppressed and is typically the weak interaction, the relic density can be naturally obtained just like in the MSSM. At the same time, the singlet-like Higgs bosons, not so related to electroweak symmetry breaking, can be light enough to be kinematically chosen to decay dominantly into muons or electrons. The Sommerfeld enhancement needed in the dark matter annihilation for the explanation of PAMELA result can be induced by exchanging the light CP-even singlet-like Higgs boson.

In this review, we recapitulate the recent studies on the dark matter explanation in supersymmetric models. In Sec.II we discuss the MSSM. In Sec.III we discuss the NMSSM and nMSSM. In Sec.IV we focus on the general singlet extension of the MSSM. Finally, a summery is given in Sec. V.

## II. NEUTRALINO DARK MATTER IN MSSM

The MSSM is the most economical realization of supersymmetry, which has the minimal content of particles. Among the four neutralinos (the mixture of neutral gauginos and neutral Higgsinos), the lightest one is usually assumed to be the lightest superparticle (LSP). Due to the R-parity conservation assumption, the neutralino LSP is stable. Since it has weak interaction and its mass is around weak scale, it is a perfect WIMP. The neutralino LSP mainly annihilates to final states consisting of heavy quarks or gauge and/or Higgs bosons, as shown in Fig.1.

With current experimental constraints which are from the precision electroweak measurements, the direct search for sparticles and Higgs bosons, the stability of Higgs potential and the muon $g-2$ measurement, a scan over the parameter space (see the last reference in [9]) found that a large part of the parameter space can give the required dark matter relic density. If we project the allowed parameter space in the plane of $\tan\beta$ versus $\mu$, it is shown in Fig.2.

In the constrained MSSM like mSUGRA, the parameter space allowed by the explanation of dark matter relic density is usually displayed in the plane of $m_0$ versus $m_{1/2}$, which showed that there exist several regions to give the required dark matter relic density [12].

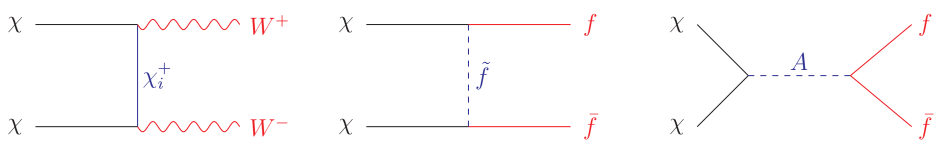


FIG. 1: Feynman diagrams of the main annihilation channels of the neutralino LSP in the MSSM.

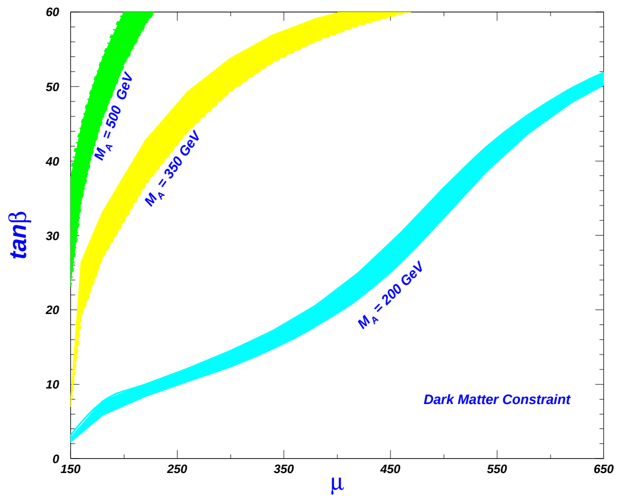


FIG. 2: The shaded regions are allowed by the cosmic dark matter relic density at $2\sigma$ level plus other experimental constraints in the MSSM, taken from the last reference in [9].

Although both the neutralino LSP in the MSSM and the constrained MSSM can naturally explain the dark matter relic density, the PAMELA result cannot be explained. As shown in Fig.1, the annihilation final states consist of heavy quarks or gauge bosons, and, therefore, if it predicts positron excess, it must simultaneously lead to antiproton excess. Meanwhile, there exist no light scalar or gauge bosons to induce the Sommerfeld enhancement.

## III. NEUTRALINO DARK MATTER IN NMSSM AND nMSSM

Both the NMSSM and nMSSM extend[1] the MSSM by adding a singlet Higgs superfield $\hat{S}$. The difference of the two models is that the superpotential contains a trilinear singlet term $\kappa\hat{S}^3$ in the NMSSM, which is replaced by a tadpole term $\xi_F M_n^2 \hat{S}$ in the nMSSM. There is no $\mu$ term in the superpotential and such a $\mu$ term is dynamically generated through the coupling between the two Higgs doublets and the newly introduced singlet Higgs field which develops a vacuum expectation value of the order of the SUSY breaking scale. Thus the $\mu$ problem is solved in both models. The little hierarchy problem can also be alleviated because on the one hand the LEP II lower bound on the mass of the SM-like Higgs boson $h$

is relaxed by the suppressed $ZZh$ coupling and/or by the suppressed visible decay $h \to b\bar{b}$, on the other hand the tree-level upper bound on the Higgs boson mass $m_h$ is pushed up.

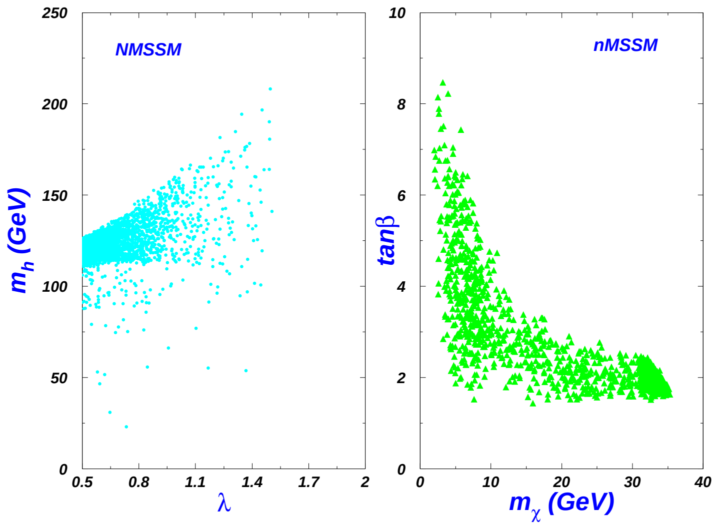


FIG. 3: The shaded regions are allowed by the cosmic dark matter relic density at $2\sigma$ level plus other experimental constraints in the NMSSM and nMSSM, taken respectively from the last reference in [9] and [10].

In both models the neutralino LSP has a large component of singlino (the fermion component of $\hat{S}$), which serves as the dark matter particle and can explain the dark matter relic density measured by WMAP. With current experimental constraints which are from the precision electroweak measurements, the direct search for sparticles and Higgs bosons, the stability of Higgs potential and the muon $g-2$ measurement, a scan over the parameter space was performed for the NMSSM (see the last reference in [9])) and the nMSSM (see the last reference in [10]). It was found that in both models there exist a large part of the parameter space which can yield the required dark matter relic density. In Fig.3 we show some results from the scan.

As shown in Fig.3, the neutralino LSP in the parameter space allowed by the dark matter relic density cannot explain the PAMELA result because in the NMSSM the lightest CP-even Higgs boson cannot be light enough to induce the Sommerfeld enhancement (the neutralino may explain either the relic density or PAMELA, but impossible to explain both via Sommerfeld enhancement [13]) while in the nMSSM the neutralino mass is restrained in a narrow range.

## IV. DARK MATTER IN GENERAL SINGLET EXTENSION OF MSSM

In the general singlet extension of the MSSM the Higgs superpotential contains both the $\mu$ term and all possible terms of the singlet superfield. So this model can only solve the little hierarchy problem but suffers from the $\mu$ problem. The dark matter candidate is the singlino-like neutralino LSP which annihilates to the light singlet-like Higgs bosons $h$ (CP-even) or $a$ (CP-odd), as shown in Fig.4, and the relic density can be naturally obtained from the weak interaction between singlino and singlet Higgs bosons. Due to the vast parameter space, the singlet-like Higgs bosons $h$ and $a$ can be light enough to be kinematically restrained to decay dominantly into muons or electrons, as shown in the left panel of Fig.5 The Sommerfeld enhancement can be induced by exchanging the light singlet Higgs boson $h$ and for a light enough $h$ such an enhancement can be quite large, as shown in the right panel of Fig.5. With

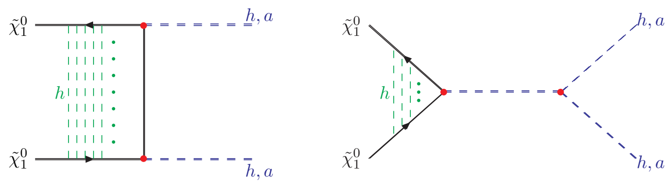


FIG. 4: Feynman diagrams for the singlino-like neutralino dark matter annihilation where Sommerfeld enhancement is induced by exchanging a light CP-even Higgs boson $h$.

the muon final states of the neutralino annihilation and the large Sommerfeld enhancement induced by a light $h$, the PAMELA result can be explained in this model [11]. A scan showed [11] that in the allowed parameter space the SM-like Higgs boson $h_{SM}$ tends to decay into the singlet Higgs pairs $aa$ or $hh$ instead of $b\bar{b}$. So the $h_{SM}$ produced at the LHC will give a multi-muon signal, $h_{SM} \to aa \to 4\mu$ or $h_{SM} \to hh \to 4a \to 8\mu$.

## V. CONCLUSION

We briefly reviewed the supersymetric explanation for the cosmic dark matter. The neutralino in the MSSM, NMSSM and nMSSM can naturally explain the dark matter relic density, but it can hardly explain the PAMELA result. In the general singlet extension of the MSSM, both the PAMELA result and the relic density can be explained simultaneously by the singlino-like neutralino which annihilates into the singlet-like Higgs bosons. These singlet-like Higgs bosons are light enough to decay dominantly to muons or electrons, and the

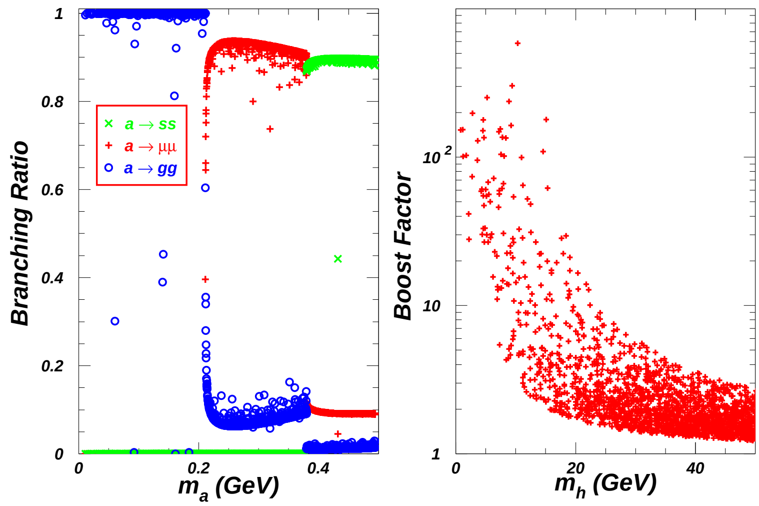


FIG. 5: The left panel is the scatter plots showing the decay branching ratios $a \to \mu^+\mu^-$ (muon), $a \to gg$ (gluon) and $a \to s\bar{s}$ ($s$-quark). The right panel is the scatter plots showing the Sommerfeld enhancement factor induced by $h$. These results are taken from the second reference in [11].

annihilation cross section can be greatly enhanced by the Sommerfeld effect via exchanging a light CP-even singlet-like Higgs boson. In this scenario, in order to meet the stringent LEP constraints, the SM-like Higgs boson tends to decay into the singlet Higgs pairs instead of $b\bar{b}$ and consequently it will give a multi-muon signal $h_{SM} \to aa \to 4\mu$ or $h_{SM} \to hh \to 4a \to 8\mu$ at the LHC.

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